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DESIGN OF AN AC-DIPOLE FOR USE IN RHIC*

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Abstract

We present two options for implementing a pair of AC-dipoles in RHIC for spin flipping, measuring linear optical functions and nonlinear diagnostics. AC-dipoles are magnets that can be adiabatically excited and de-excited with a continuous sine-wave in order to coherently move circulating beam out to large betatron amplitudes without incurring emittance blow up[1]. The AGS already uses a similar device for getting polarized proton beams through depolarizing resonances[2]. By placing the magnets in the IP4 common beam region, two AC-dipoles are sufficient to excite both horizontal and vertical motion in both RHIC rings. While we initially investigated an iron-dominated magnet design, using available steel tape cores; we now favor a new air coil plus ferrite design featuring mechanical frequency tuning, in order to best match available resources to demanding frequency sweeping requirements. Both magnet designs are presented here along with model magnet test results. The challenge is to make AC-dipoles available for year 2000 RHIC running.

1 AC-DIPOLE REQUIREMENTS

AC-dipole operating frequency is application dependent. When used with polarized protons as a spin flipper, the frequency is swept in the vicinity of the spin tune, i.e. $\approx 0.5\times f_{rev}$, or specifically 37 ± 2 kHz for RHIC. Linear optics measurements can use a constant frequency excitation at either 15 or 63 kHz but sweeping is needed for nonlinear optics measurements. An integrated field strength of $\approx$300 gauss·m is needed but $\pm$3% field inhomogeneity is tolerable. Since the RHIC injection kicker ceramic beam pipe assembly (length $\approx$1.3 m) fits twice in the available IP4 space and has sufficient (42 mm) inner aperture, it will also be used for the AC-dipoles to save on spares.

Since high frequency currents flow mostly on conductor outer surfaces due to the skin effect, we intend to use Litz wire. Litz wire has many fine strands twisted and braided together so as to link the same magnetic flux. This arrangement yields a uniform current distribution across the conductor cross section. Therefore, the Litz AC-resistance is $\approx$DC value for dramatically lower power dissipation as compared to a solid conductor. Round Litz cable, made from #38 gauge (0.1 mm diameter) copper wire is sufficiently fine for our application and the cable is easily bent in any plane (helpful for forming coil ends).

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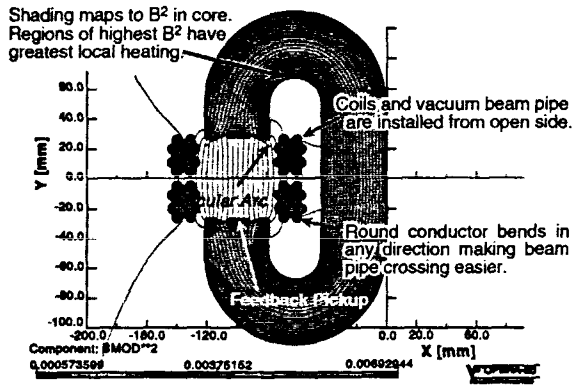

Figure 1. C-magnet made from Litz wire and tape-wound steel C-core. Each half coil has 12 turns of #6 Litz wire. Field uniformity is better than 0.5% at 10 mm radius.

Initially we focused on using #6 Litz wire coils in an iron-dominated C-magnet due to the availability of unused tape wound cores (left over since 1981 after construction of the Fermilab Main Ring Abort Kickers). These cores consist of 3% silicon steel tape, 0.05 mm thick, wound in a racetrack configuration. The small lamination thickness reduces eddy current effects in these cores and makes them suitable for short period pulses.

2 C-CORE MAGNET DESIGN

The proposed C-core magnet cross section is shown in Opera-2d[3] output plot in Figure 1. The C-geometry returns magnetic flux along a low reluctance path and thereby reduces the amp·turns needed for a given field strength, compared to an air coil magnet. It also permits easy installation of the vacuum beam pipe and coils through the gap. In an iron-dominated magnet, the field shape is largely determined by the pole configuration. For the $\approx$300 gauss field strength, saturation is not an issue; therefore, the pole face is recessed to achieve desired field quality. This pole shape has been produced via an initial straight cut followed by fine milling along a circular arc on a numerically controlled milling machine.

From the average core B^2 calculated in Opera-2d, we can estimate the core eddy current losses. Since higher B^2 areas contribute more to losses, the coil configuration and pole gap were optimized to reduce average B^2. Experience with similar laminated materials shows that core losses should scale as $f^{1.6}$ (i.e. between hysteresis linear with f and f^2 from eddy currents). In practice even the estimated 63 kHz loss of $\approx$2.4 kW is much smaller than anticipated external circuit losses in frequency sweeping components. At 15 kHz the 200 W estimated core loss is $\approx$1/3 the resistive losses of an equivalent air coil due to the C-magnet's more efficient use of excitation current.

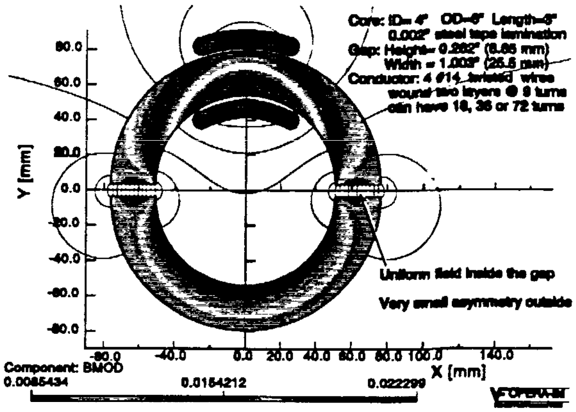

Figure 2. AC-dipole test magnet cross section.

3 TEST MAGNET MEASUREMENTS

Since 15 and 63kHz are nearly equivalent for beam dynamics, the originally specified ±5kHz frequency tuning seemed easier to achieve as a ±8% spread at 63kHz than as a much larger ±33% spread at 15kHz; however, would eddy currents reduce or distort the field in the gap more at the higher frequency? In order to address this concern we constructed a small test magnet using a pair of 0.05 mm lamination semicircular tape cores as indicated in the Opera-2d output shown in Figure 2. The test magnet has a dual 6.7 mm gap and a tight fitting fixture was made for positioning a small 6-turn probe coil inside the magnet. Because the 30 mm probe coil length is much less than the 76 mm core length, magnet end effects are small. The 6.7 to 26 mm gap to pole width ratio yields a uniform central field which can be reasonably mapped with the 3 mm wide probe coil.

The impedance of the test magnet was matched to 50Ω by a capacitor network and verified via network analyzer. Reproducible probe coil placement was possible via scribe lines at 19 measurement positions. Since probe response is proportional to frequency, the probe signal was divided by frequency in comparing scans (yielding a frequency normalized transfer function). The excitation current was measured by two methods which agreed to better than 0.3%. Repeat field maps are practically indistinguishable. Test magnet field maps were measured 9 times at 66.26, 15.(×2), 10.(×2), 5.(×2), 0.97 and 0.5 kHz.

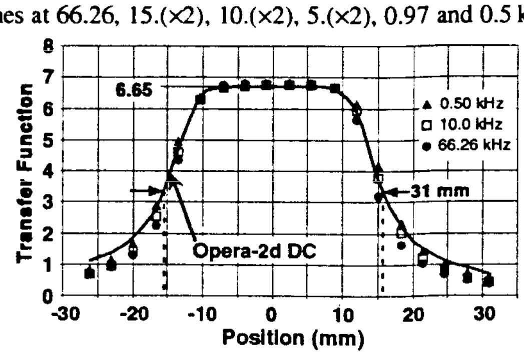

Figure 3. Comparison of measured transfer function for DC (Opera-2d prediction) and f = 0.5, 10 and 66.26kHz.

The central transfer function was found to be constant to 0.8% and agreed with an Opera-2d static prediction to ≈2% using uncalibrated geometric areas.

A comparison for three frequencies is shown in Figure 3. The fringe field drops relative to the central field with increasing frequency. When all measurements for a given frequency are summed to yield an integrated transfer function (ITF), a 7% average ITF drop with frequency is observed between 500Hz and 66.26kHz. This drop is consistent with the ≈15% magnet inductance change measured separately.

4 FREQUENCY TUNING SCHEMES

One difficult AC-dipole design challenge is to sweep the oscillation frequency quickly during nonlinear measurements and spin flipping. The originally requested ±33% tuning (15±5 kHz) was deemed too difficult; however, we did analyze power supply schemes capable of yielding 39±5kHz (spread equiv. to 63±8kHz). A simple but very brute force approach is to add sufficient circuit dissipation (dummy loads) to reduce system Q to 4 for broad band frequency response. Then a pickup coil inside the magnet gap can be used for amplitude feedback. While the circuitry for this scheme is quite simple, a 100kW vacuum tube based power supply is needed.

Instead of spoiling Q, a variable series inductance could be included in the circuit. Here we could borrow existing water-cooled ferrite cores (50cm OD, 4L2 grade) and wind 9 pairs, first with alternate bias turns, and then common magnet excitation turns. Frequency response is then proportional to bias current; unfortunately, significant energy dissipation in the ferrite cores still requires a 20kW vacuum tube for ±5kHz and these relatively expensive cores would some day have to be purchased or returned.

An alternate tuning approach is to vary the AC-dipole inductance directly. The C-cores, in which the AC-field is rapidly cycling back and forth, could have a large perpendicular DC bias field applied to them. The bias field would partially saturate the C-cores and thereby modify the inductance of the magnet. Varying the bias field alters the resonant frequency. The system frequency thus follows the bias field as long as the Q is not too high compared to the rate of change (i.e. analogous to cavity filling time). Unfortunately, steel is not an optimum material for this scheme since very large bias fields are then needed. Configurations with ferrite yokes were also investigated; however, it was not found possible to make large inductance changes and simultaneously maintain adequate field quality and low AC-losses with reasonable ferrite geometry.

5 AIR COIL PLUS FERRITE OPTION

While investigating ferrite plus air coil inductance biasing schemes we realized that the magnet stored energy was much more sensitive to ferrite position than to ferrite

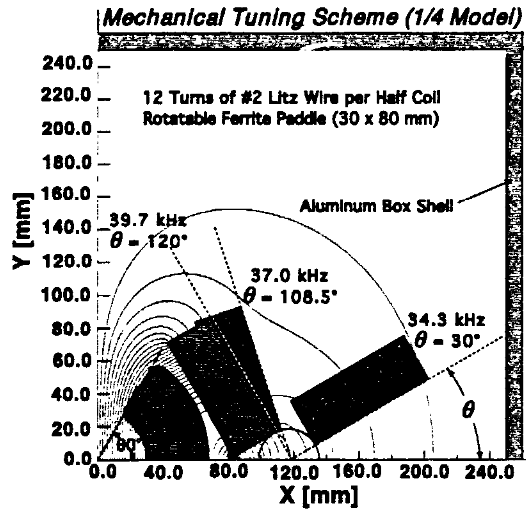

Figure 4. Magnet with variable reluctance frequency tuning. Scheme uses air coil plus movable ferrite insert. Magnet inductance changes as ferrite angle is varied.

permeability. Even pulling the ferrite's relative permeability down to $\mu=4$, which would require a large bias current, is not as effective as moving the ferrite away from the coil (i.e. getting $\mu=1$). Our latest scheme, shown in Figure 4, starts from an approximate cos-theta current distribution (i.e. $\approx 60°$ half angle) for each 3-layer half coil using 12 turns of Litz wire. To partially offset the increase in excitation current needed to achieve the same central field with the air coil's poor transfer function, #2 (6 mm OD) Litz wire is needed.

Introduction of the ferrite tile close to the coil decreases the stored energy (or inductance) by more than 30%, so there is potential for ±7% tuning about a central resonant frequency. For mechanical simplicity the ferrite tile is rotatable about a pivot point (note that only 1/4 of the model is shown in Figure 4, so there are actually four ferrite tiles which must be moved symmetrically). The relationship between the ferrite angle and system resonant frequency is shown in Figure 5. We find that most of the tuning range is covered by 90° motion from 120° to 30°.

The few parts per mil field quality achievable with this system, shown in Figure 6, is much better than needed and it is clear that final field quality will be dominated by

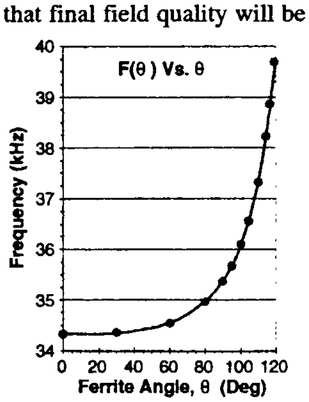

Figure 5. Relationship between ferrite angle and system frequency for mechanical tuning scheme described above.

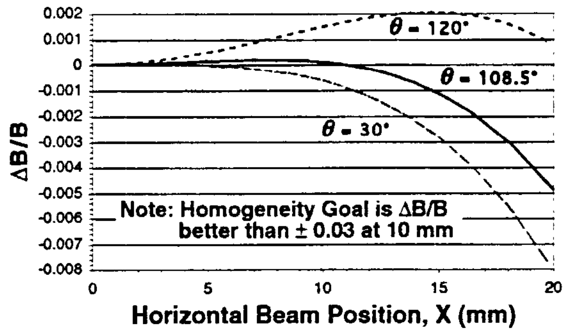

Figure 6. Field quality achievable with mechanical tuning. The curves shown span the intended tuning range.

the coil end effects and construction errors. A simple servomotor plus computer interface system already exists which could be adapted to move the ferrite tiles either under direct computer control or via a programmable logic system. The servomotor and belt drive system can be mounted on the outside of an aluminum box. The box serves to shield the magnet from external influences and to contain otherwise annoying AC fringe fields. Estimates indicate that eddy current losses in the ferrite tiles and box walls are small compared to dissipation in the coil and matching capacitor network.

We hope to run the system frequency control almost open loop and use pickup coils above and below the beam pipe for amplitude feedback. We anticipate that a medium conductance path should also be provided, close to the beam pipe, for passing the two beam image currents in order to avoid wake field trapping.

6 CONCLUSIONS

Although tests indicate that the tape wound core design would be suitable for meeting AC-dipole requirements, when evaluating a complete system, cost and schedule considerations favor using the variable magnetic reluctance path mechanical frequency tuning scheme described above. Implementation of this scheme, denoted here as air coil plus ferrite in a box, should be possible for use during RHIC year 2000 running; however, there are still many details which must be worked out.

7 ACKNOWLEDGMENTS

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[3] Vector Fields Inc., 1700 N. Farnsworth Ave., Aurora, IL 60505.